

Magnetic Fields Across the Hertzsprung-Russell Diagram
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Magnetic flaring in pre-main sequence stars

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Abstract. Observations of nearby star forming clouds with imaging X-ray telescopes have revealed that X-ray emission is elevated $10^1 - 10^4$ above main sequence levels in low-mass pre-main sequence (PMS) stars. The variability and spectral X-ray evidence, together with circularly polarized radio continuum flares seen in a few cases, strongly argues for an origin in magnetic reconnection flares. These high levels of magnetic activity are present from the earliest protostellar phase to the main sequence. After a brief review of past observations, three astrophysical issues are raised: the location of the flaring magnetic fields, the origin of these fields, and the effects of flare high-energy photons and particles on the environs. New results from Chandra observations of a well-defined samples of PMS solar analogues are presented, giving an improved view of magnetic flaring in the early Sun.

1. Introduction

In his discovery paper of low-mass pre-main sequence (PMS) stars among the Taurus-Auriga dark clouds, the T Tauri variables, Albert Joy (1945) drew a connection between their unusual spectra and the solar chromosphere. In the following decades, hundreds of "flash variable" low-mass stars were reported in Orion and other star-forming regions (Haro & Chavira 1966). But study of magnetic activity played a relatively minor role in the interpretation of young stellar objects compared to the attention paid to emission lines associated with outflows into and inflows from the circumstellar environment (e.g. Herbig 1962; Hartmann 1998).

The presence of high levels of magnetic activity and flaring was reasserted with the discovery of bright and highly variable X-ray emission from PMS stars obtained with imaging X-ray telescopes. These X-ray luminous stars included both classical T Tauri stars and similarly young stars without broad emission line spectra (Feigelson & DeCampi 1981; Feigelson & Kriss 1981). The latter "weak-lined" T Tauri (WTT) stars are late-type, lithium-rich stars displaying a variety of manifestations of enhanced magnetic activity: variable X-ray emission $10^1 - 10^4$ times levels typically seen in older main sequence stars; cool starspots covering large fractions of the stellar surface evidenced by photometric rotational modulations or spectroscopic Doppler imaging; variable H α and Mg II in emission from plage and chromosphere; and, in some cases, U-band photometric flares, variable circularly polarized radio continuum flares, and Zeeman splitting

of photospheric absorption lines. WTT stars are sometimes clustered around star forming molecular clouds along with CTT stars, and sometimes dispersed tens of parsecs from older star formation events such as the Sco-Cen OB Association and the Gould Belt. These findings are detailed in a review by Feigelson & Montmerle (1999).

Here we examine in some detail one aspect of the magnetic activity of young low-mass stars: the violent magnetic reconnection flares. We start with portraits of two flaring T Tauri and protostars from X-ray and radio studies (§2). Three astrophysical issues arising from such observations are outlined (§3). We then turn to an ongoing study of a well-defined sample of PMS solar analogues using the recently launched Chandra X-ray Observatory (§4).

2. Portraits of two flaring PMS stars: V773 Tau and YLW 15

Perhaps the most magnetically active star in the nearby Taurus-Auriga star forming cloud complex, V773 Tau = HD 283447 is a hierarchical triple system of three roughly solar-mass stars with age $\simeq 1$ Myr. The system appears to be transitional between the CTT and WTT phases. Its "quiescent" X-ray emission is very high $\simeq 1 \times 10^{31}$ erg/s in the soft X-ray band (0.5-2.4 keV), about 10^4 times the level of the contemporary Sun, with $\log L_x/L_{bol} \simeq -3$ at the "saturation level" of late-type stars.

The ASCA satellite provided detailed views of two X-ray flares from V773 Tau during 1995. One event showed a modest elevation in flux in the soft X-ray band (0.5 – 2 keV) but a factor > 50 rise in the hard band (2 – 8 keV) followed by an exponential drop in flux with a decay timescale of 2.3 hours (Tsuboi et al. 1998). The inferred plasma temperature at the flare peak was thus extremely high, $T(\text{peak}) \simeq 100$ MK with $\log L_x(\text{peak}) \simeq 33.0$ erg/s and total energy release $\log E_x \simeq 37$ ergs in the X-ray band. The decay phase is reasonably well-modeled by simple quasi-static cooling of a uniform plasma where the volume emission measure $EM \propto T^3$. For this model, the electron density is inferred to be $n_e \simeq 3 \times 10^{11} \text{ cm}^{-3}$ with a loop length $\simeq 4 \times 10^{11} \text{ cm} \simeq 2 R_*$. The second ASCA flare had somewhat lower peak emission with $T(\text{peak}) \simeq 40$ MK and $\log L_x(\text{peak}) \simeq 32.3$ erg/s, but a longer flux decay over > 20 hours (Skinner et al. 1997). A short-lived reheating (or separate flare) event was seen during the decay. The temperature and flux decay phase can be roughly modeled by either a quasi-static cooling loop or a two-ribbon long-duration solar flare model. Another possibility is rotational eclipsing of a continuously emitting loop near the rotational pole with height around $0.6 R_*$.

Both members of the V773 Tau close binary are strong nonthermal radio emitters, as directly imaged with VLBI techniques. On one occasion, a radio flare was seen with the Very Large Array showing both linear and circular polarization, indicating acceleration of electrons to supra-relativistic energies during the flare (Phillips et al. 1996). Radio and X-ray flaring are decoupled from each other. While V773 Tau is particularly well-studied, WTT stars with similar extremely high magnetic activity include V410 Tau and HDE 283572 in Taurus-Auriga, DoAr 21 in Ophiuchus, and Parenago 1724 in Orion. Simple models of single magnetic loops consistently suggest enormous loop size of several stellar radii.

The molecular cores of the nearby ρ Ophiuchi cloud is the richest cluster of young stellar objects within $\simeq 200$ pc of the Sun. In addition to dozens of T Tauri stars are several embedded Class I protostars. YLW 15 = IRS 43 is one of the youngest and most luminous of these protostars with $L_{bol} \simeq 10 L_{\odot}$ and estimate age of $\simeq 0.1$ Myr. It is surrounded by a dense dusty envelope $\simeq 3000$ AU in radius and produces a small bipolar CO outflow with an ionized region around the protostar seen in radio continuum.

Its magnetic activity was first detected in soft X-rays during an intense flare with the ROSAT satellite, rising by a factor > 20 and decaying with an e -folding time of 5 hours (Grosso et al. 1997). A long ASCA exposure revealed a sequence of three flares separated by $\simeq 20$ hours (Tsuboi et al. 2000). Each showed a fast rise to a peak $\log L_x \sim 32$ erg/s, followed by an exponential decay with timescales of 8 – 18 hours. The plasma cooled during the decays from a peak $T \simeq 60$ MK. The total energy of the flare sequence in the X-ray band was $\log E_x \simeq 37.0$ ergs. As with the WTT stars, interpretation based on radiatively cooling loops imply loop lengths $l \simeq 1 \times 10^{12}$ cm and plasma densities comparable to those in solar flare ($n_e \sim 10^{10} \text{ cm}^{-3}$). Montmerle et al. (2000) develop the idea that the reconnection field lines connect the protostar to the circumstellar disk near the star-disk corotation radius; such field lines will be continuously twisted by the Keplerian velocity shear in the disk. The model parameters indicate a protostar with mass $M_* \simeq 2 M_{\odot}$ and radius $R_* \simeq 5 R_{\odot}$ rotating rapidly with period $P_* \simeq 10$ hours linked to the inner disk at $R_{disk} \simeq 2 R_*$ with a much slower orbital period $P_{disk} \simeq 4$ days. They suggest that YLW 15 is in the early stages of star-disk magnetic braking. Radio continuum emission seen from the system is interpreted as thermal emission from coronal-temperature plasma ejected by the reconnection events, not nonthermal emission as in V773 Tau.

3. Three astrophysical issues

3.1. What is the magnetic field geometry producing young stellar flares?

The basic concept of angular momentum transfer from the protostar to the disk via star-disk magnetic fields (Königl 1991), adapted from interactions between neutron stars and their accretion disks, is widely accepted, and the theory for accretion and generation of collimated outflows from the corotation radius is well-developed (e.g. Shu et al. 1994). Considerable empirical evidence supports this star-disk magnetic interaction model including interpretation of optical emission lines and outflow properties for T Tauri stars (e.g. Hartmann 1998; Feigelson & Montmerle 1999; Guenther, this volume).

The question is whether these star-disk fields are responsible for the magnetic flaring seen with X-ray and radio telescopes, as in the model of YLW 15 outlined above. Even after magnetic braking is largely complete, fluctuations in accretion plausibly can lead to field reconnection, as indicated in magnetohydrodynamical simulations. The high $L_x(\text{peak})$ and $L_r(\text{peak})$ luminosities together with the long durations of PMS flares compel extremely large magnetic structures that extend far beyond the stellar surface if one assumes a simple model of an isolated magnetic loop with a single injection of magnetic energy undergoing radiative cooling.

The uncertainty in this model arises because long-duration flares are seen in the Sun and, with comparable luminosities, in some RS CVn-type magnetically active stars which do not involve links to a circumstellar disk. In long-duration solar flares which last many hours, energy is stored in a complex of magnetic structures which are released sequentially. In some cases a single loop is repeatedly reheated, while in other cases motion or eruption of one structure causes a flare in a nearby structure. The flares of WTT stars, which presumably are no longer interacting with a disk, are similar in duration and power to protostellar flares. As there is a broad consensus that WTT activity is due to solar-type flaring in multipolar structures attached to the stellar surface, it is plausible that this is the only geometry producing flares in even the youngest PMS stars. (See the Discussion below for additional comments on this issue.)

3.2. Does PMS magnetic activity arise from a solar-type dynamo?

There are profound reasons, both astrophysical and observational, to believe that a magnetic dynamo is the source of surface activity on the Sun and in main sequence late-type stars (Cattaneo, Dikpati, Knoelker, Charbonneau, this volume). The same processes should be present in PMS stars which have mostly or fully convective interiors and are rotating more rapidly than most main sequence stars. It seems implausible that PMS stellar interiors rotate as perfect solid bodies to avoid the twisting and amplification of fields which generate stellar dynamos.

Yet, the few available observational diagnostics of the origin of PMS activity provide a muddled picture and do not clearly support the dynamo model. The relationship between X-ray emission (measured either by X-ray luminosity or X-ray surface flux) and stellar rotation (measured either by spectroscopic surface velocities or photometric rotational periods P_* , or Rossby number) is either weak or absent in available samples. In particular, slowly rotating PMS stars are often seen at very high X-ray levels (Figure 1). This dramatically contrasts with main sequence stars where, for solar-mass stars in the range $3 < P_* < 30$ days, X-ray luminosity is anti-correlated with rotational period according to $\log L_x \simeq 31.0 - 2.6 \log P_*$ (Güdel et al. 1997). Instead of a $L_x - P_*$ association, the principal correlations seen in PMS samples are $L_x - L_{bol}$ (characteristic of OB stars, not late-type, main sequence stars) and $L_x - M_*$ (Feigelson et al. 1993). The situation is poorly understood, as it is difficult to untangle interwoven effects of luminosity, age, mass and rotation in PMS stars.

3.3. What are the effects of flares on the circumstellar environment?

Some of the most important astrophysical implications of PMS flaring may involve the impact of flare products on ambient material. These include keV-energy photons as seen with X-ray telescopes, MeV-energy particles as evidenced by gyrosynchrotron emission in PMS stars, and shocks that are likely to accompany the violent reconnection events. These effects are complex and, in most cases, their role is quite uncertain. These issues are discussed in some detail by Glassgold et al. (2000).

PMS X-rays, both during flares and quiescence, must impact some part of the circumstellar disks and partially ionize the largely neutral material. As the geometry of the X-ray emitting magnetic structures is uncertain (§3.1), it

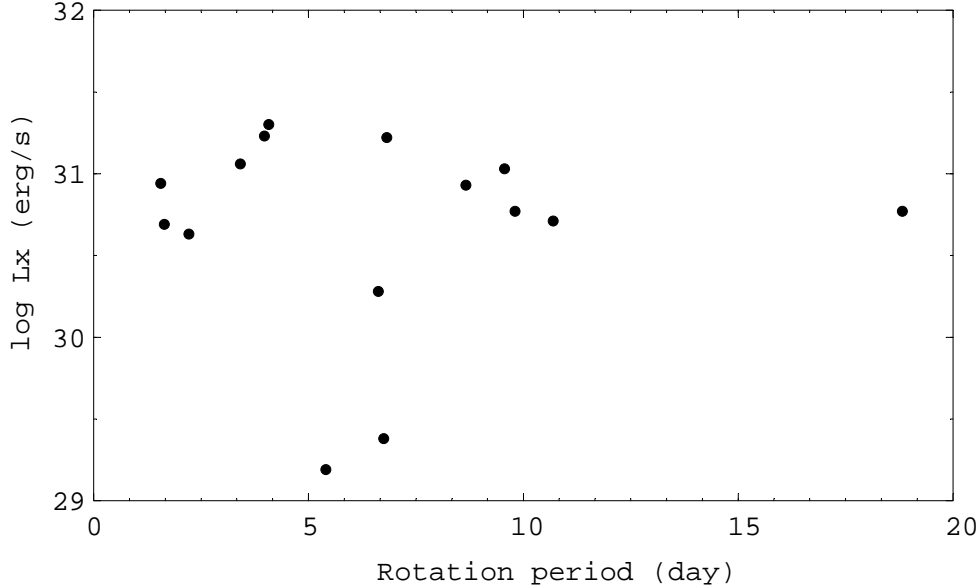


Figure 1. Relationship between X-ray luminosity L_x (0.5 – 8 keV band) and rotational period P_* measured from photometric modulation of starspots for PMS analogues of the Sun. It does not show the anti-correlation seen in main sequence stars and expected from the magnetic dynamo model. The sample shown here is discussed in §4. (*Feigelson et al., in preparation*)

is unclear whether large portions of the disk will in fact be irradiated. There is some empirical evidence for X-ray irradiation of the disk: a 6.4 keV fluorescent emission line from neutral iron seen in flare of protostar R1 Cr A (Koyama et al. 1996), and excited molecular lines in the disk of TW Hya (Weintraub et al. 2000). It is possible that this ionization will induce magnetohydrodynamical behavior, such as the magneto-rotational (Balbus- Hawley) instability, which in turn would stimulate turbulent viscosity, accelerate angular momentum transport within the disk, and promote accretion onto the young star. Ionization of the outer layers of the disk may also be critical for coupling the Keplerian rotation of disk material to the collimated outflows characteristic of protostars and CTT stars.

For deeply embedded PMS stars, X-rays must ionize some molecules in the surrounding cloud. If these X-ray Dissociation Regions (Hollenbach & Tielens 1997) extend over sufficiently high over sufficiently large volumes of the cloud, then ambipolar diffusion of the neutral gas through cloud magnetic fields will be impeded and subsequent star formation in the cloud may be delayed. There is as yet little astronomical evidence yet for XDRs around flaring PMS stars.

Gyrosynchrotron emission from MeV electrons have been seen in dozens of flaring PMS stars, mostly WTT stars but in one case a Class I protostar (Feigelson & Montmerle 1999). If the acceleration processes are similar to those seen in solar flares, relativistic protons and other nuclei will also be produced which will bombard some portion of the disk. There is good evidence that this process

occurred in the early solar nebula: certain grains in carbonaceous chondrites exhibit both unusually high levels of particle tracks and spallogenic ^{21}Ne which can only be plausibly explained by exposure to very high MeV particle fluences prior to compaction into the host meteorite (Woolum & Hohenberg 1993). With less confidence and more controversy, PMS flare protons may also account for some or all of the remarkable high abundances of short-lived nuclides (e.g. ^{26}Al , ^{41}Ca) found in carbonaceous chondrites (Feigelson 1982; Lee et al. 1998).

Finally, the shocks and radiation produced by PMS flares may provide the sudden heating that melted dustballs in the solar nebula, producing the chondrules found in great abundance in stony meteorites. Shu et al. (1997) develop such a scenario that accounts for a variety of chondrules properties, including mass sorting in different meteorites. Many other models for chondrules melting have been suggested, and as yet none has gained widespread acceptance.

4. Chandra study of solar analogues in the Orion Nebula Cluster

The Chandra X-ray Observatory, launched in July 1999, has a unique combination of capabilities for the study of X-ray emission from young stars, particularly those that are in young clusters still embedded in their molecular cloud. Its superb mirrors provide arcsecond imaging and reflectivity up to $\simeq 8$ keV; the CCD detectors of the ACIS detector provide extremely low noise, high quantum efficiency and moderate spectral resolution; and the high-Earth orbit permits long uninterrupted observations of variable phenomena. Young stars can be detected with as few as 7 counts during day-long exposures, and embedded objects are seen with absorptions up to $A_V \simeq 50 - 100$ magnitudes.

A prime Chandra target is the Orion Nebula Cluster (ONC), a dense cluster of $\simeq 2000$ stars with masses ranging from 0.02 to $50 M_\odot$ and ages from $\simeq 0.1$ to $\simeq 10$ Myr which illuminates the famous Orion Nebula. Early findings are reported by Garmire et al. (2000) and Schulz et al. (2001). Nearly all of the $M \geq 1 M_\odot$, and a large fraction of the lower-mass stars, are detected with ACIS – this image with $\simeq 1000$ X-ray stars is the richest field of sources ever obtained in X-ray astronomy.

Here I present preliminary results concerning a well-defined subsample of ONC stars that can be considered analogues of the early Sun (Feigelson et al., in preparation). It consists of all ONC stars with $V < 20$ and $0.7 < M < 1.4 M_\odot$. Thirty-nine of these 41 stars are detected with ACIS; most are extremely strong with > 1000 photons detected in two $\simeq 12$ hr exposures separated by several months. Luminosities are measured from plasma fits to the ACIS spectra in the $0.5 - 8$ keV band assuming a distance of 450 pc.

A wide range of variability characteristics are seen among these solar-mass PMS stars: some show constant emission while about $1/3$ exhibit powerful short-timescale flares during the two 12-hour observations. These flares have a wide range of properties: $30 < \log L_x(\text{peak}) < 32$ erg/s; $34 < \log E_x < 36$ erg, and durations from 40 minutes to > 12 hours. Most, but not all, show spectral hardening around peak flux and softening during the decay phase. Prominent flares are seen in both CTT and WTT solar analogues, and in stars of all ages from ~ 0.1 to ~ 20 Myr. Figure 2 shows three of these flares. The top panel is an extremely young WTT star with flare showing $\log L_x(\text{peak}) \simeq 32.0$ erg/s and

$E_x > 36.2$ erg. The middle panel is an intermediate-age CTT star with flare showing $\log L_x(\text{peak}) \simeq 31.4$ erg/s and $E_x \simeq 34.7$ erg. The bottom panel is an older CTT star with flare showing $\log L_x(\text{peak}) > 31.5$ erg/s and $E_x > 35.7$ erg. CTT (classical T Tauri) and WTT (weak-lined T Tauri) classification is based on K-band infrared excess. No obvious relationship between flare characteristics and stellar age, rotation or disk emission is apparent.

The time-averaged X-ray emission of the sample declines with stellar age: $\log L_x$ falls from about 31 to 29 – 30 erg/s over a few Myr. This can be readily explained as a combination of magnetic saturation, where virtually the entire surface of the star is covered with magnetic structures, and the declining surface area as the star evolves down the convective Hayashi track. These very young stars all have $\log L_x/L_{bol} = -3.5 \pm 0.5$, near the upper envelope of L_x/L_{bol} seen in magnetically active main sequence stars. After 1 – 2 Myr, the dispersion in X-ray emission appears to increase: some stars remain with $\log L_x/L_{bol} \simeq -3.5$ (indeed, a few become even more active with $\log L_x/L_{bol} \simeq -2$), while in others the X-ray emission declines to $\log L_x \leq 29$ erg/s and $\log L_x/L_{bol} \leq -4.5$. This phenomenon might be understood in the context of models of the rotational evolution of PMS stars (Bouvier et al. 1997) combined with simple dynamo concepts. Stars which remain rotationally coupled during the descent of the Hayashi track will be slow rotators and, would display low levels of magnetic activity like X-ray luminosity, while stars that decouple early from their disks will spin up as they contract and display high X-ray levels. However, we do not see the anti-correlations between circumstellar disks or rotational periods and X-ray emission in these solar-mass PMS stars (Figure 1). The situation is thus confused, and the data conceivably may falsify the magnetic dynamo model along the PMS convective tracks.

Importantly, since our sample is complete, we can be fairly confident that the behavior seen in ONC solar analogues represents behavior exhibited by the early Sun. Several consequences of this solar-stellar link emerge. First, during the first 1 – 2 Myr, the surface of the young Sun was "saturated" with magnetic fields which heated plasma to temperatures ≥ 10 MK emitting 0.5–8 keV X-rays at levels of $\log L_x \simeq 31$ erg/s and $\log L_x/L_{bol} \simeq -3.5$. Afterwards, during the 2 – 20 Myr period, we cannot determine if the Sun's activity remained at high levels or decreased by 1 – 2 orders of magnitude. During the entire PMS era, the early Sun produced a flare at levels $\log L_x \geq 30$ erg/s and $\log E_x \geq 34$ erg every few days. For comparison, the contemporary Sun produces a long-duration flare 10^2 weaker roughly every 10^3 days (viz. the 1992 Nov 2 flare).

These results provide the first *quantitative* determination of the activity and flaring levels in the early Sun based on astronomical measurements of a well-defined sample of young solar analogues. They can be used to evaluate the importance of local high energy photons and particles on the solar nebula: ionization of gas, charging of dust grains, spallation of nuclei in meteoritic solids, and flash melting of chondrules.

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Discussion

PRIEST: It is worth examining whether solar flares can be scaled to give the observed T Tauri flare properties (see E. Priest and T. Forbes, *Magnetic Reconnection*, Cambridge Univ Press, 2000). For example, 10^{37} ergs seem enormous to a solar physicist, but in the Sun the energy scales as $B^2 l^3$ so that field strengths (B) and sizes (l) that are both a factor of 10 higher would produce the PMS flare. Also, on the Sun, the ‘decay’ time is certainly not the radiative cooling time. It has proved very difficult to build a realistic solar flare model: having X-points and reconnection is not sufficient since reconnection can occur continuously, and the presence of an instability is not sufficient since it may saturate. One needs to demonstrate how energy can slowly build up and then suddenly be released, as in the magnetic catastrophe model. So perhaps some of the solar flare experience can help with understanding your PMS flares.

SCHMITT: On the issue of the location of CTT flares, in a flare on Algol with $E_{bol} > 10^{37}$ ergs similar to CTT stellar flares, the X-ray emission was eclipsed (Schmitt & Favata, *Nature* 401:44, 1999). This shows the flaring plasma to be near the pole and with limited height. The flare energetics can be explained by reconnection of magnetic fields of approximately 1 kG in the corona. Thus, in my opinion, there is no need to invoke star-disk interactions in CTT stars.

FEIGELSON: Both of these points are cogent criticisms of the frequent use of the over-simplified quasi-static cooling loop model for PMS stellar flares. Dr. Schmitt’s argument is discussed in more detail by F. Favata (in *X-ray Astronomy 2000*, R. Giacconi et al. eds, in press). It is difficult to discriminate between large star-disk and compact star-star loop flares from the existing data. There is hope that more detailed spectral studies (e.g. of the fluorescent Fe-K α 6.4 keV line from disk reflection) may provide critical clues.

LINSKY: You asked whether PMS flares occur close to or far from the star. One test is to study the change in metal abundance: for RS CVn systems, metal abundances increase during flares presumably due to evaporation of material from the photosphere or chromosphere. Can this be done for PMS flares?

FEIGELSON: A valuable thought, particularly in light of the dramatic abundance variations during stellar flares found with XMM (Brinkman et al., *As&Ap* 365:L324, 2001). With ACIS alone, it is difficult to make detailed statements about individual elemental abundances, but abundance study of a bright PMS stars with the Chandra or XMM gratings is definitely warranted.

VAN BALLEGOOIJEN: Are there simultaneous observations of X-ray and H α flares in pre-main sequence stars?

FEIGELSON: Simultaneous X-ray, optical/UV and radio measurements have been made for a few stars (e.g., Feigelson et al. *ApJ* 432:373, 1994; Guenther et al. *As&Ap* 357:206 2000). Generally there is no relation between X-ray and radio flares, but a weak correlation between X-rays and H α may be present.

PISKUNOV: In the case of long duration soft X-ray events in CTT stars, how can you tell a flare from variability in the mass accretion rate?

FEIGELSON: It is doubtful that a significant fraction of observed X-rays comes from accretion, as the observed X-ray temperatures are typically 10 – 30 MK (and higher during powerful flares) compared to ~ 1 MK expected from the accretion shock (e.g. Lamzin et al., *As&Ap* 306, 877, 1996).

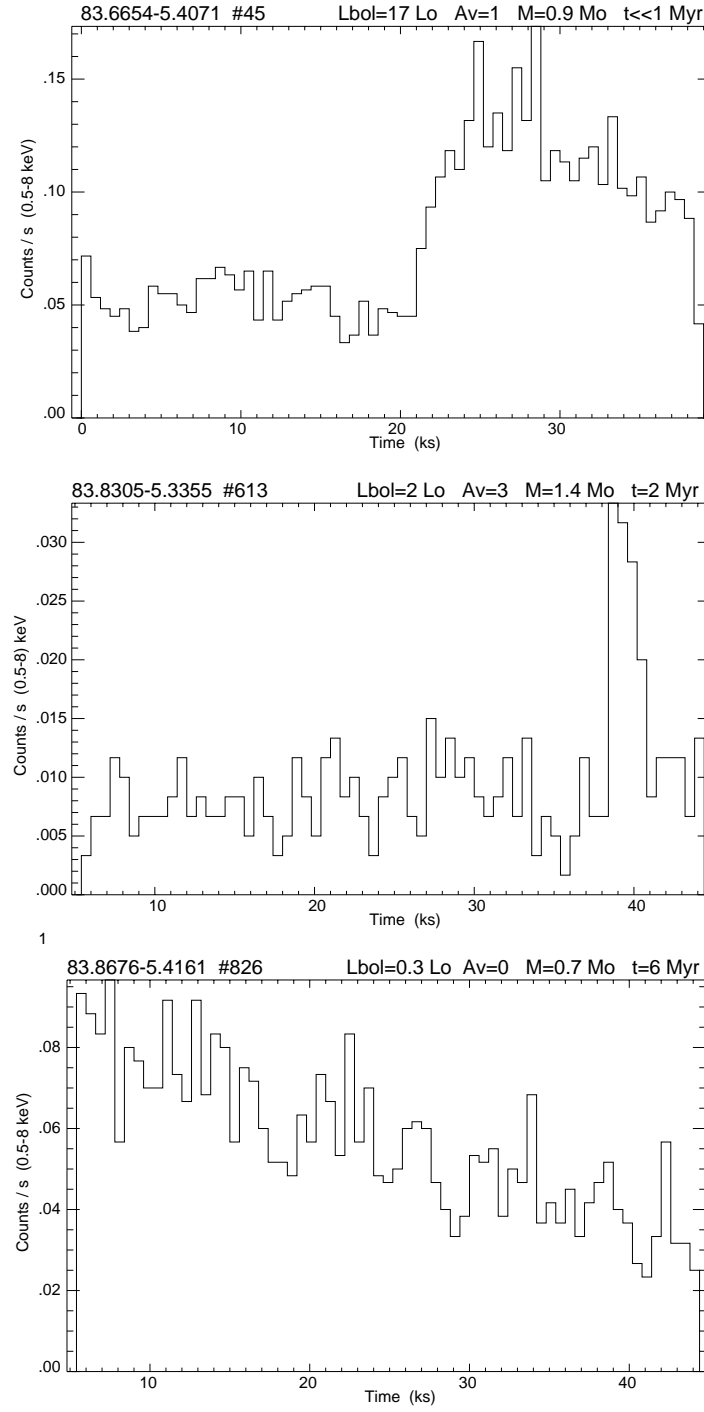


Figure 2. X-ray lightcurves from the Chandra X-ray Observatory observations Orion Nebula Cluster, illustrating the range of flares present in PMS solar analogues. Each panel is labeled by the stellar counterpart, bolometric luminosity, visual absorption, mass and age. The duration of each light curve is about 12 hours. (*Feigelson et al., in preparation*)